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Red LED Strip Signalling Pedestrian Presence at Uncontrolled Mid-block Crosswalks

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Abstract

A relevant number of collisions between vehicles and pedestrians occur at night because of the reduced capacity of a driver to perceive and react to the presence of pedestrians at crosswalks. To reduce this risk of collision, new smart road technologies have been introduced. This study aims to evaluate the effectiveness of a red LED strip that warns the driver of the presence of pedestrians at unsignalized mid-block crosswalks at night-time. The technology consists of LED strips installed near the crosswalk on the side of oncoming vehicles. The LED is activated when a sensor detects a pedestrian approaching the crosswalk. In this driving simulation experiment, three different urban mid-block crosswalks were evaluated: (i) without an LED strip (baseline), (ii) with a fixed LED strip, and (iii) with a flashing LED strip. Each scenario was tested for three different levels of pedestrian time gap acceptance (PTGA) (i.e., 4, 6, 8 s) and two road sections (i.e., 1 lane vs. 2 lanes). Thirty-six participants took part in a within-subjects' design. During the experiment, the minimum time to collision (mTTC), the post-encroachment time (PET), maximum vehicle speed, and reaction distance were monitored to quantitatively compare the different levels of vehicle-pedestrian interaction. Compared to the baseline, the LED strip resulted in a safer driver-pedestrian interaction, with an average increase in mTTC of 1.13 s, PET of 0.66 s, and a longer average reaction distance of 7.9 m. However, a slight (albeit not statistically significant) increase in speed was observed following installation of the LED strip. Furthermore, no significant differences were observed between fixed and flashing LED strips. Overall, these results confirm the LED strips effectiveness in alerting the driver to the presence of a pedestrian, thus increasing the safety of their interaction. Further studies should confirm these findings in a more ecological way, e.g., evaluating the safety impact of this technology under different weather and distracted driving conditions.

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Keywords: *Smart Road Technologies; Pedestrians; Surrogate Safety Measures; Driver Behavior; Road Safety; Driving Simulation*

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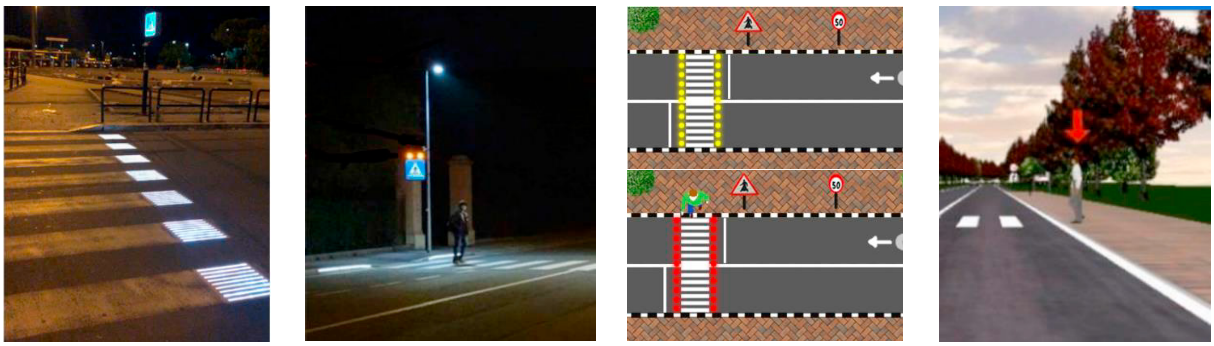
1. Introduction

The Decade of Action for Road Safety 2021-2030 (WHO, 2021) sets the ambitious target of preventing at least 50% of road traffic deaths and injuries by 2030. Worldwide, road traffic crashes cause more than 1.3 million preventable deaths and an estimated 50 million injuries every year – making it the leading cause of death for children and people aged 5-29 worldwide. Within these statistics, vulnerable road users (VRU), i.e., pedestrians, cyclists, two-wheelers and persons with disabilities, account for more than 50% of all road traffic deaths, with many of these occurring in urban areas. Another aspect meriting careful consideration is the number of collisions at night between vehicles and VRU, mainly due to poor visibility and insufficient lighting conditions that negatively affect the braking reaction of drivers (Owens and Sivak, 1996; Plainis, 2006; Sullivan and Flannagan, 2002).

Literature has paid special attention to pedestrian safety at mid-block crosswalks where they are most at risk of colliding with vehicles. In recent years, research has focused on using smart technologies as a safety countermeasure. Some technologies are able to detect the presence of conflicting road users and alert drivers in advance. A solution has been proposed by Patella et al., (2020) with the LED-lit pedestrian crossing. They installed and tested this technology in Rome (close to the "Anagnina" subway). The smart crossing, consisting of panels containing 9 LED stripes (Fig. 1a), contributed to a 19.3% reduction in average vehicle speed, reducing the hazardousness of the conflict. Flashing in-curb LED strips and beacons (Fig. 1b) installed and tested in Bologna (Italy) at unsignalized pedestrian crossings have been proposed by Lantieri et al., (2021). This solution significantly increased the yield compliance and pedestrian detection distance. Hussain et al., (2023, 2021) tested the effectiveness of a system called ITS_LED (Fig. 1c) and observed a positive increment in yielding rates and a reduction in the vehicle-pedestrian conflict severity. Augmented reality (AR) in-vehicle technologies have also been used to increase driver awareness of the presence of pedestrians. A study by Calvi et al., (2020) tested the effectiveness of an AR system alerting the driver to a pedestrian ahead by placing a red arrow on the head of the pedestrian (Fig. 1d). The results were positive with drivers starting to slow down well before the crossing when the AR was active, with high time-to-collision and time-to-zebra values.

Although smart crosswalks have been explored in literature, the majority remain purely conceptual with little information on their impact on the behaviour, acceptance, and mental workload of drivers with a notable lack of information on the safety effectiveness of LED strip crosswalks. LED strips are installed along crosswalks and alert drivers to the presence of crossing pedestrians. It is worth noting that any smart technology, including LED strips, should not replace basic road safety hardware such as lighting, road markings, and pedestrian signs, which should be considered standard safety installations.

In this study, we evaluated the effectiveness of red LED strips at uncontrolled mid-block crosswalks on urban roads at night. In this regard, the LED strip was tested with two light configurations. i.e., fixed and flashing at a 2Hz frequency, and then compared with a traditional uncontrolled crosswalk (the baseline). The proposed technology was aimed at reducing the hazardousness of conflicts between vehicles and pedestrians.



(a) (b) (c) (d)

Fig. 1. Case (a) crosswalks was proposed by Patella et al., 2020, with crosswalk delimited by LED panels installed at the edges of each zebra crossing. The LED lights switch on when a pedestrian passes under the optical sensor. Case (b) was proposed by Lantieri et al., 2021, with in-curb LED strips that were activated by a movement sensor, a "yield here to pedestrians" sign, orange beacons positioned above the sign, and LED lamps. Case (c) was proposed by Hussain et al., (2023), with a smart detection-based-in-pavement LED light unit. This system warned drivers when a pedestrian was detected along the road. In the first situation (without pedestrians), the yellow LED light flashes. When a pedestrian is detected at the edge of the crosswalk the same strip changes to flashing red lights. Case (d) was proposed by Calvi et al., (2020), with AR warning systems implemented in the driving simulator to alert drivers to a pedestrian on the sidewalk. The visual warning system consisted of a red arrow above the pedestrian which tracks the pedestrian during the crossing.

2. Method

2.1. Participants

Thirty-six participants (11 females) were randomly selected from a database of more than 500 available participants recruited with a message disseminated through the social media of the Politecnico di Torino. The sample included drivers aged between 24 and 51 (mean = 30.7, SD = 6.6). All drivers voluntarily took part in the activity without receiving any monetary compensation. The experiment was conducted in compliance with the World Medical Association's Code of Ethics (WMA, 2013). The drivers were unaware of the hypothesis under investigation.

2.2. Experimental design

The experiment was conducted following a within-subject design with 3 experimental factors: (i) LED strip, (ii) pedestrian time gap acceptance (PTGA), and (iii) the road section type. The LED strip was the main factor and was tested under three different conditions: (i) no LED strip along the crosswalk (baseline), (ii) LED strip with fixed lights and (iii) LED strip with flashing lights. For the PTGA, the three values of 4, 6 and 8 s already used by Angioi and Bassani (2022) were adopted. PTGA is the time gap from when the pedestrian started crossing the road to when the vehicles reached the conflicting point in the crosswalk. PTGA can be viewed as an indicator of pedestrian aggressiveness: the smaller the PTGA, the higher the risk assumed by the pedestrian in traversing the road in front of the oncoming vehicle. Finally, to account for the change in driver behaviour on different road types, measurements were taken along road segments with (i) one and (ii) two lanes per direction.

From a combination of these factors, three urban scenarios were designed. The first involved crosswalks with no LED strip and a combination of the other experimental factors (3 PTGA × 2 road sections). The second scenario included crosswalks with fixed LED strips and the same combination of the other two factors. The third scenario consisted of crosswalks with flashing LED strips and, again, the same combination of the two other experimental factors.

We monitored surrogate measures of safety like the (i) maximum speed of vehicle recorded from 100 m before the crosswalk, (ii) the distance from the crosswalk at which the driver reacts to the presence of the pedestrian (reaction distance) by acting on the brake pedal, (iii) the minimum time-to-collision (mTTC) between vehicle and pedestrian, and (iv) the post-encroachment time (PET). We also evaluated the effects of the LED strips on subjective mental workload using the NASA-TLX questionnaire.

mTTC is the minimum time (i.e., the most critical) remaining before a collision between two moving entities that occurs if they continue on their intended path with the same speeds and trajectories (Hayward, 1971). In our study, we considered a TTC of 3 s to discriminate between cases where drivers unintentionally find themselves in a dangerous situation (i.e., conflict) and cases where drivers remain in control.

PET represents the time difference between a dynamic entity leaving the area of encroachment and another dynamic entity entering the same area (Peesapati et al., 2018). Three categories for PET can be identified according to Angioi and Bassani, (2022): (i) undisturbed passage for PET ≥ 5 s, (ii) conflict 0 < PET ≤ 5 s, and (iii) crash when PET = 0 s.

2.3. Equipment and simulated scenarios

The experiment was conducted at the Road Safety and Driving Simulation (RSDS) Lab of Politecnico di Torino. The Scenario and simulations were designed using SCANeR Studio (https://www.avsimulation.com/scanerstudio/). Table 1 lists the specification of the driver simulator used.

We designed an urban road setting with a speed limit of 50 km/h with three segments, two two-lane (one per direction) and one four-lane (two per direction with median), for a total length of 7.3 km. A number of crosswalks, spaced 600 m apart on average in the two-lane and 400 m in the four-lane segments, were included. Lane width was set at 3.0 m for the two-lane section, and 3.5 m for the four-lane section. The horizontal and vertical signs conformed to the rules of the Italian Highway Code, (1993). To reproduce a realistic urban environment, we also included vehicles, and pedestrians moving around without interfering with the driver. In all three scenarios, other mid-block crosswalks with and without pedestrians were included with the purpose of confusing the driver and creating unpredictable situations for them.

We monitored only those crosswalks where pedestrians arrived from the right side. In this experiment this was the most hazardous situation because of (i) the shorter arrival time to the potential conflict zone and (ii) the obstructed visibility of pedestrians from the driver point of view due to parked cars close to the crosswalks (see Figure 2). In this experiment, pedestrians started crossing at PTGA values of 4, 6, or 8 s distributed randomly across the events. Experimental factors were randomly generated not only between scenarios but also between participants to prevent any learning effect bias. In the two scenarios with LED strips, the LED switched on when the driver neared the crosswalk and the pedestrian started to cross. The colour red was adopted since it conveys danger in traffic signs and lights (Chapanis, 1994). Fig. 2 shows three examples of the road scenarios featuring a pedestrian crossing the road.

Table 1. Specifications of the fixed-base driving simulator.

Computers and monitors	Hardware	Software
CPU: Quad-core **Video Card**: NVIDIA GeForce® GTX 1070 **Memory**: 16 Gb of random-access memory **Monitor**: Full HD curved 32:9 ultra-wide-angle 49-inch (resolution 3840 x1080) with 144 Hz refresh rate	**Cockpit**: Car seat, steering wheel, manual gearbox, pedals. **Interactions between vehicle and road**: Steering wheel returns active force feedback to the driver, simulating wheels' rolling, pavement roughness, and shocks.	**SCANeR^{TM} Studio**: Design tracks, manage the vehicle parameters, generate the experimental scenarios, run the simulations, collect and extract data

(a) **(b)** **(c)**

Fig. 2. Crosswalks (a) without, (b) with fixed LED strips and road section with one lane per direction, and (c) with fixed LED strips and road section with two lanes per direction. In the fixed LED condition, the pedestrian crossed the road with the led bar always on. In the flashing condition, the bar operated with a flashing light at a frequency of 2 Hz. The light was activated when the pedestrian stepped inside an area monitored by a set of virtual cameras.

2.4. Procedure and statistical analysis

The procedure included the following steps: (i) a pre-drive questionnaire, (ii) a pre-drive test of 5 min, (iii) the three-driving simulations, (iv) the NASA-TLX questionnaire between each drive, and (v) the post-drive questionnaire. The pre-drive questionnaire collected demographic data, driving information, and health condition status. Subsequently, participants underwent a trial scenario to gain familiarity with the simulator. After a rest period of 2 minutes, the participants were then asked to drive the three experimental scenarios, which were administered in a different order following the complete counterbalance method (composed of six possible combinations (3!)), in order to avoid any familiarity bias. At the end of each drive, participants completed the NASA-TLX questionnaire followed by a rest time of at least one minute before starting the next drive. The experiment ended with a post-drive test collecting information on the driving experience at the simulator and the state of health after completing the experiment.

Statistical analyses on the collected data were performed using Jamovi software version 2.2.5. Five repeated ANOVA measurements were taken. We checked the normality, sphericity, and randomness assumptions. The significant threshold (α) was set equal to 0.05. When a significant effect was found, Bonferroni post-hoc tests were performed.

3. Results

The ANOVA results are reported in Table 2. The statistical analysis of the NASA-TLX questionnaire is reported in section 3.5. The results for each analysis are commented on in the following sections.

Table 2. RM-ANOVA results on max vehicle speed 100 m before the crosswalks (Speed), reaction distance, minimum time to collision (mTTC), and post-encroachment time (PET); depending on LED, Lane (Cross section), PTGA and interactions.

	Speed [km/h]			Reaction distance [m]			mTTC [s]			PET [s]		
	F	df	*p*	F	df	*p*	F	df	*p*	F	df	*p*
LED	3.58	(2,70)	**.033**	3.11	(2,34)	.058	6.52	(2,70)	**.003**	6.46	(2,70)	**.003**
Cross section	18.81	(1,35)	**<.001**	5.78	(1,17)	**.028**	1.58	(1,35)	.217	16.31	(1,35)	**<.001**
PTGA	3.44	(2,70)	**.038**	72.12	(2,34)	**<.001**	130.5	(2,70)	**<.001**	11.79	(2,70)	**<.001**
LED × Cross section	3.78	(2,70)	**.028**	4.58	(2,34)	**.017**	6.75	(2,70)	**.002**	4.59	(2,70)	**.013**
LED × PTGA	1.11	(4,140)	.356	3.92	(4,68)	**.006**	0.07	(4,140)	.990	3.01	(4,140)	**.020**
Cross section × PTGA	0.41	(2,70)	.668	0.21	(2,34)	.809	0.63	(2,70)	.538	0.38	(2,70)	.686
LED × Lane × PTGA	1.31	(4,140)	.271	0.77	(4,68)	.546	0.78	(4,140)	.537	1.81	(4,140)	.131

3.1. Max speed in the 100 m leading up to the crosswalk

The maximum speed recorded (Fig. 3) in the 100 m leading up to the crosswalk was significantly affected by LED ($p = .033$), as well as by PTGA ($p = .038$). There was also a significant main effect for the cross section ($p < .001$) with participants driving slower with one lane (-2.01 km/h) compared to two lanes. In addition, the interaction between LED and cross section was significant ($p = .028$). However, Bonferroni-corrected post hoc analysis did not reveal significant differences between the baseline and fixed LED ($p = .107$), and between the baseline and flashing LED conditions ($p = .066$). For the post hoc comparisons on PTGA, we found significant differences between PTGA of 4 s and 8 s (*mean difference* 1.057, $p = .046$).

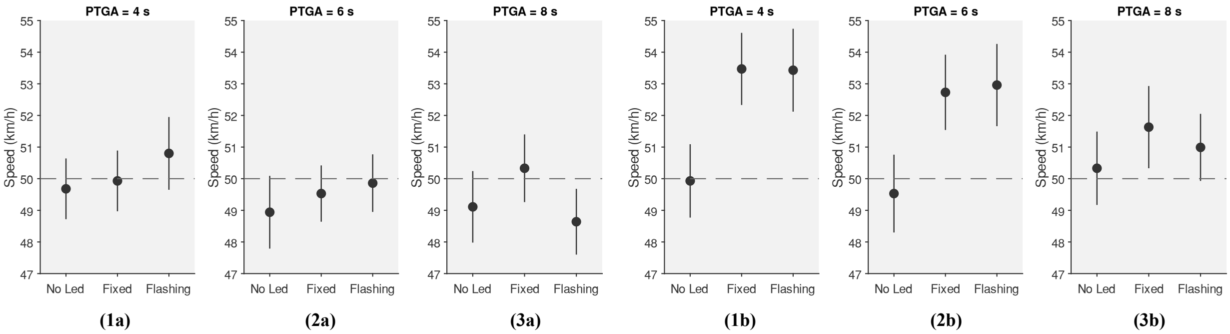


Fig. 3. Maximum speed recorded in the 100 meters before the pedestrian crossing with (a) one-lane and (b) two lanes per direction. (1) PTGA = 4 s; (2) PTGA = 6 s; (3) PTGA = 8 s. The dots represent the average value, while the lines represent the standard error of the mean. The dashed lines represent the posted speed limit = 50 km/h.

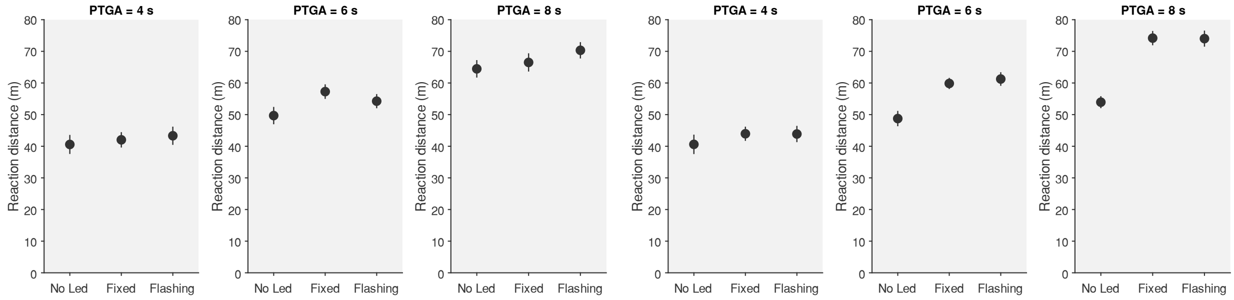
3.2. Reaction Distance

The reaction distance of participants (Fig. 4) was significantly influenced by cross section ($p = .028$) and PTGA ($p < .001$). The LED had a significant effect on the interaction with cross section ($p = .017$) and PTGA ($p = .006$). Post-hoc comparisons revealed significant differences in the two-lane configuration between baseline and fixed LED (*mean difference* = - 11.0 m, $p = .015$) and between baseline and flashing LED (*mean difference* = - 11.4 m, $p = .031$).

3.3. Minimum time to collision (mTTC)

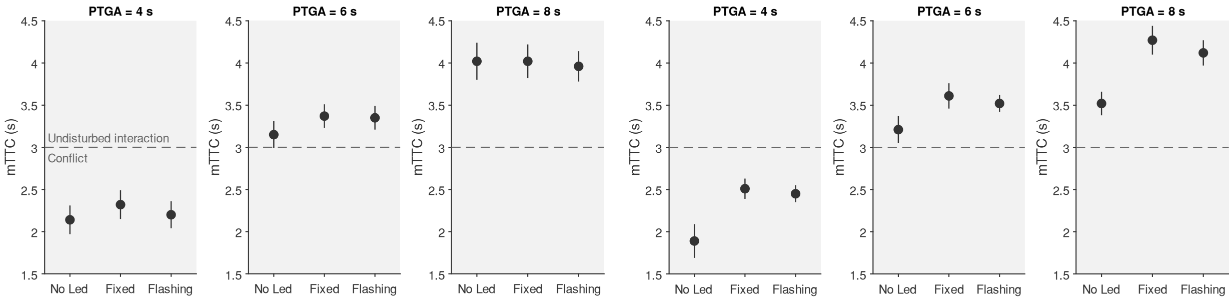
The minimum time to collision between vehicle and pedestrian (Fig. 5) was significantly influenced by the LED factor ($p = .003$), indicating that the LED conditions had a significant impact on the observed outcomes. Post hoc comparisons revealed further significant differences between the baseline and fixed LED (*mean difference* = -0.362,

p = .009) as well as between the baseline and flashing LED (*mean difference* = -0.279, p = .032). However, no significant difference was found between the fixed and flashing LED strips. There was also a significant main effect for the factor PTGA ($p < .001$). Post hoc comparisons for PTGA revealed significant differences between the 4 s and 6 s interaction (*mean difference* = -1.116, $p < .001$) as well as between 4 s and 8 s (*mean difference* = -1.732, $p < .001$). Additionally, a significant difference was observed between the 6 s and 8 s conditions (*mean difference* = -0.616, $p < .001$).



(1a) (2a) (3a) (1b) (2b) (3b)

Fig. 4. Reaction distance with (a) one-lane and (b) two-lanes per direction. (1) PTGA = 4 s; (2) PTGA = 6 s; (3) PTGA = 8 s. The dots represent the average value while the lines represent the standard error of the mean.



(1a) (2a) (3a) (1b) (2b) (3b)

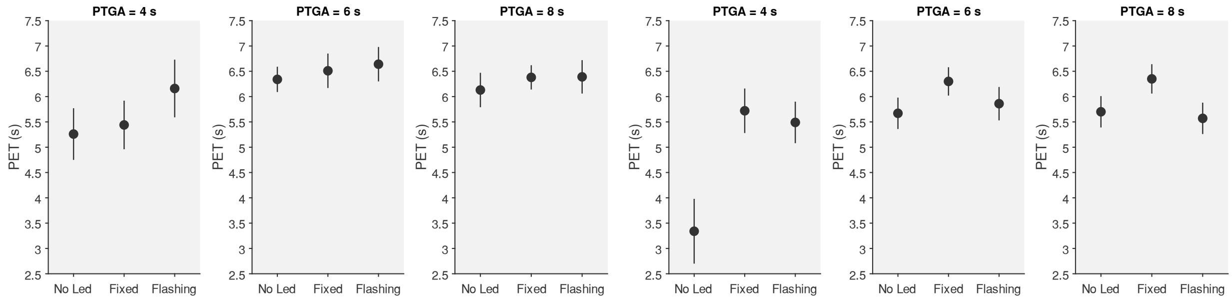
Fig. 5. Minimum time-to-collision (mTTC) with (a) one-lane and (b) two lanes per direction. (1) PTGA = 4 s; (2) PTGA = 6 s; (3) PTGA = 8 s. The dots represent the average value, while the lines indicate the standard error of the mean. The dashed lines represent the threshold (i.e., 3 s) between undisturbed interaction and conflict.

3.4. Post encroachment time (PET)

The analysis revealed that the different LED conditions had a significant impact on PET outcomes (p = .003, Fig. 6). Post hoc comparisons for LED demonstrated significant mean differences between the baseline and the fixed LED conditions (*mean difference* = -0.706, p = .007), as well as between the baseline and the flashing conditions (*mean difference* = -0.612, p = .033). Moreover, the analysis revealed a significant main effect of cross section ($p < .001$), and of the PTGA ($p < .001$). Post hoc comparisons for PTGA revealed significant mean differences between the 4 and 6 s interaction between the driver and the pedestrian (*mean difference* = -0.983, p = .003), as well as between 4 and 8 s (*mean difference* = -0.851, p = .003).

3.5. NASA-TLX questionnaire

Repeated ANOVA measurements revealed a significant main effect of LED on mental workload ($F(2,70) = 8.96$, $p < .001$). Post hoc comparisons indicated a significantly lower mental workload in the Fixed LED condition (p = 0.001) and in the Flashing condition (p = 0.028) compared to the baseline (unlit crosswalk). No significant difference in mental workload was found between the fixed and flashing conditions (p = 0.338).



(1a) (2a) (3a) (1b) (2b) (3b)

Fig. 6. PET with (a) one lane and (b) two lanes per direction. (1) PTGA = 4 s; (2) PTGA = 6 s; (3) PTGA = 8 s. The dots represent the average value, while the lines indicate the standard error of the mean.

4. Discussion and conclusion

The results indicate that the LED strips led to a slight increase in the maximum speed in the 100 m before the crosswalks: while this increment was not significant on the one-lane road and drivers remained close to the posted speed limit (50 km/h), it was more pronounced on the two-lane road, with an average speed increment of 2.6 km/h. These results are consistent with those of Lantieri et al. (2021), who found no significant differences between the speed values observed with the standard and LED crosswalks (Fig. 1b). The PET results showed that drivers waited longer before resuming their driving after stopping at a pedestrian crossing with LED strips. This is in accordance with the results of a study conducted in Qatar which found a significant improvement in PET with the ITS_LED solution (Hussain et al., 2023). We believe that this result is explained by the higher speed of certain drivers who, especially in the case of the crosswalks marked with LED strips, waited longer before driving away, and then tried to make up for lost time by increasing their speed between consecutive crosswalks. However, the slight increase in speed did not undermine the overall level of safety, as the drivers exhibited enhanced responsiveness to the stimuli generated by the LED lights. Despite their marginally higher velocity, they demonstrated a heightened ability to react promptly, thereby maintaining a safe behaviour.

The analysis of the reaction distance highlighted the significant impact of PTGA. As the PTGA increases, so does the reaction distance, allowing the driver to perceive the crossing pedestrian earlier and to react in time. This finding is consistent with the study by Angioi and Bassani, (2022), who observed an increase in reaction distance as the PTGA increased. It is important to note that the effect of LED strips was more pronounced when PTGA increases because the LED strip itself lights up earlier as the pedestrian begins crossing. In this case, the driver immediately notices the light signalling the presence of the pedestrian and reacts earlier. Vice versa, when the PTGA was set to 4 s, the driver had already seen the pedestrian when the lights turned on to signal their presence on the crossing. Therefore, in that case, the LED strip did not have a significant impact.

The analysis of mTTC revealed an increase in mTTC when the fixed and flashing LED strips were active compared to the case of unlit crosswalks. This outcome supports the hypothesis of a reduced probability of collision in vehicle-pedestrian interactions thanks to the investigated technology. The results of Calvi et al., (2020) corroborate our conclusions, since they observed that when the presence of a pedestrian is highlighted the values of TTC increase with respect to the baseline condition. When the pedestrian time gap acceptance (PTGA) was set to 4 s, all interactions resulted in conflicts with mTTC < 3 s. However, with the LED strip, the mTTC increased significantly thus indicating a relevant improvement in safety. With PTGA set to 6 and 8 s, the interactions no longer constituted conflicts as the mTTC was always greater than 3 s. Even in those situations, the LED strip had a strong influence, increasing the mTTC values compared to the unlit condition. The interaction between LED lighting and cross-section revealed a significant difference between the baseline and LED strips in the two-lane segments. This outcome can be explained by the fact that drivers on two-lane roads benefited not only from the LED strips, which influenced their longitudinal behaviour, but also from the wider lateral space within the roadway. This additional space enabled them to maintain a greater distance from potential conflicts.

From the subjective perspective, the lower perceived mental workload revealed by the NASA-TLX questionnaire suggests that the LED strips at crosswalks are intuitive and user-friendly, thus they could be accepted by drivers on roads. The reduced mental workload indicates that the message conveyed is clear and helpful and encourages a prompt reaction to the presence of a pedestrian. Together with the positive response from surrogate safety measures already discussed, the LED strips have the potential to significantly improve safety at crosswalks. Indeed, when drivers are less mentally burdened, they can devote more attention to their surroundings, and identify other potential hazards. Finally, our analysis revealed no significant differences between fixed and flashing LED strips, suggesting that the presence of emitting lights did not exert any discernible influence on the perceived mental workload.

Taken together, the results of this study strongly support the conclusion that LED strips, both fixed and flashing, effectively improve the safety of pedestrian crossings at night. By increasing driver responsiveness, improving reaction distances, and providing an increased buffer zone for potential conflicts, LED strips prove to be a tangible and practical measure to reduce the risks associated with vehicle-pedestrian interactions. Therefore, the implementation of LED stripes at uncontrolled mid-block crosswalks is recommended as a strategy to improve pedestrian safety and promote the well-being of both pedestrians and drivers. It is important to acknowledge that further studies are required to validate the results obtained and strengthen the conclusions drawn from this research. New studies could evaluate the potential effectiveness of the LED strips in mitigating the risks associated with more challenging situations. Additionally, it would be beneficial to explore other conditions, such as driving in fog or when distracted. These conditions represent real-world challenges on roads, and investigating the impact of LED strips under such circumstances would provide further insights into their overall effectiveness in improving road safety.

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